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Novel series fed dual band circular polarization antenna for navigational satellite system

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ABSTRACT

A novel series fed dual band stacked microstrip patch antenna (SMPA) offering circular polarization (CP) over wide beam is proposed for Indian regional navigation satellite system (IRNSS). The antenna is designed to function at far apart dual frequencies 1.176 GHz (L5 band) and 2.492 GHz (S band) intended for the receiver terminals of IRNSS system. The dual band performance with large frequency ratio (about 1:2.1) has been obtained by two stacked patches with an air layer between them. The square notches at the corners along the diagonal of lower square patch, one sided corner truncation along the diagonal of upper square patch and feeding along central axis is used to obtain CP (with axial ratio < 2) at both the operating bands. The square patches are excited with novel series feed technique. The proposed novel antenna has been designed, simulated and developed to meet the stringent design requirements for IRNSS navigation system. The antenna has achieved an impedance bandwidth of 2.6% and 2.2% at L5 and S band frequency respectively. It possesses positive gain beamwidth of 120° and 3 dB axial ratio beamwidth of 120° and 60° at L5 and S band frequencies respectively.

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1. INTRODUCTION

The global satellite navigation system (GNSS) plays a key role in modern day providing services in the domain of military, navigation to fishermen, public transport, smart vehicles, smart cities and location tracking [1]. India has developed the indigenous navigation system being called indian regional navigation satellite system (IRNSS) or navigation through indian constellation (NavIC) to provide position accuracy of up to 10 m over Indian land regions and of up to 20 m over Indian sea regions [1]. The IRNSS receiver requires single feed, compact, wide beam, low profile, dual-band circularly polarized antenna for various ground terminal applications. Dual frequencies (L5 band frequency = 1.176 GHz with 24 MHz (~2%) bandwidth and S band frequency = 2.492 GHz with 16.5 MHz (~0.66%) bandwidth have been used for better position accuracy in IRNSS system [1]. The designed antenna must be right hand circular polarized (RHCP) with low axial ratio over large coverage angular extent and shall be obtained with single feed arrangement to reduce the complexity [1]. The receiver antenna for such type of navigational system should also possess gain greater than 0 dBi for a wider beamwidth [2]. The stringent design requirements of IRNSS receiver

antenna such as dual band, wide beam circular polarization (CP) operation and compact size often place a major challenge in designing of antenna. The microstrip patch antenna has been considered a suitable choice for achieving the design goal of IRNSS or GNSS antenna since a long time.

An exhausted research has been carried out for tri band and dual band circularly polarized global positioning system (GPS) antennas [3]-[7]. But little research is presented for dual band IRNSS antenna with circular polarization operation at L5 and S band frequencies. microstrip patch antenna can obtain circularly polarization by modifying the geometry of square shaped patch and hence it is a most popular choice for a NavIC receiver due to the advantages such as planar profile, low cost, ease of fabrication, ease of integration with other circuits and useful radiation properties. In past years many have investigated variety of microstrip patch antenna based designs for suitable applications in the field of satellite and radar communication [8]-[10].

A compact single-feed stacked microstrip patch antenna (SMPA) for tri band or dual band CP application have been reported for GPS and other GNSS applications in literature. The multistacked patches fed by single coaxial probe is designed to achieve triple operating frequency bands for GPS has been proposed in [8]. The compact dual-band CP multilayered microstrip antenna based on slotting, fractal and metamaterials have been proposed for navigation satellite systems in literature [11]-[18]. All of the listed designs [11]-[18] have been able to obtain multifrequency operation but pure circular polarization operation have not been mentioned. As well, some of them use the dual feed technique whick increases the complexity of design and adds in increased size requirements.

In the latest paper of dual band NavIC receiver antenna [19]-[21] attempts have been made to realize the design requirement of IRNSS system at some extents. Design proposed in [19] has got covered only single L5 band frequency of IRNSS system and one L1 band frequency of GPS system. Till date all the reported GNSS antennas have the functioning muti-frequencies are moreover in the same operating band implying small frequency ratio between the operating frequencies [22], [23]. However, IRNSS system demand for dual frequencies in L5 and S band which are apart from each-other by large frequency difference of 1.32 MHz.

The antenna proposed in this paper is enable to get dual band operations with large frequency ratio (1:2.1) by proper selection of patch sizes, appropriate dielectric substrate thicknesses and an optimum air gap between stacked patches and single series feeding method. The variation in ratio of two stacked patch lengths and variation in air gap thickness have been parametrically analyzed to observe their impact on tuning of dual resonating frequencies. The proposed antenna is able to get wide beam gain and CP operation by appropriate selection of dielectric substrate material and with proper modification of geometries of both patches to excite the orthogonal modes with excitation time phase difference of 90° using single feed mechanism.

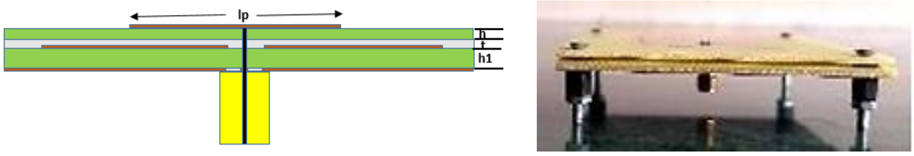
The paper is presented as per the following sections. The section 1 discusses the design requirements for receiver antenna of IRNSS system and the existing antennas designed for other GNSS system. The section 2 describes the design method of series fed SMPA and related design equations. The section 3 shows the parametric studies for proposed IRNSS antenna. The detailed simulated results of return loss, gain, axial ratio, co-polar and cross-polar patterns of proposed antenna are presented in section 4.

2. ANTENNA DESIGN METHODOLOGY

A novel design of single-feed dual-band circularly polarized SMPA with large frequency ratio between two operating frequencies is proposed. Stacked patch antennas for dual band operation have been fed with mainly 3 types in existing literature. Firstly, in two layered stacking of patches, each patch is individually fed to have resonance at each individual frequency of dual-band operation. Secondly, methodology of feeding the bottom patch only is opted where the top patch will be excited with electromagnetic (EM) coupling due to radiating bottom patch. Which may overlap two resonating frequencies and yield a wide band operation. Thirdly, new method of series feeding the stacked patches is adopted in this paper, to get dual band operation. Wherein, only the top patch developed over suitable substrate is fed with coaxial probe feeding [24]. Here the top patch dimensions are smaller and get a resonance at higher frequency of dual band operation. Whereas, the bottom patch gets excited with the EM coupling from the radiated edge-fields of top patch. Here, the bottom patch dimensions are larger and get a resonance at lower frequency of dual band operation.

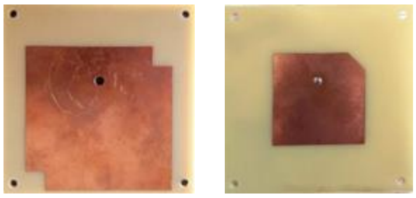
The proposed dual band antenna consists of two square patches with single feed mechanism as shown in Figure 1(a). The inner conductor of 50-Ohm coaxial probe is directly connected to the upper patch only and via hole is provided in lower patch to pass the inner conductor up to the upper patch. The two resonant frequencies are obtained by two square patches stacked upon each other and separated by an air layer of certain thickness. In the developed antenna, air layer can be created with the help of insulating spacers between two stacked patch antennas as shown in Figure 1(b). The design of upper square patch and lower square patch with modified geometries have been considered for circular polarization at both the resonating frequencies as displayed in Figure 2(a) and Figure 2(b) respectively. The simulated results show good circular polarization

performance, and large frequency ratio (1:2.1) in dual band operation is achieved. The feed point position (xf) and via-hole diameter is optimized to get the impedance match at dual band frequencies. The offset position of bottom patch relative to top patch has also impact on 10 dB return loss bandwidth at dual operating frequencies. The bottom patch is moved away from centre in order to yield better impedance matching at L5 and S band frequencies.



(a) (b)

Figure 1. Proposed geometry of dual band CP-series fed SMPA: (a) side view and (b) developed prototype



(a) (b)

Figure 2. Dual band CP-series fed SMPA: (a) upper patch design and (b) lower patch design

Empirically the design value for the length of square patch is given by [25] .
Actual length of the patch:

$$L = L_{eff} - 2\Delta L \tag{1}$$

Where $\Delta L = 0.412h \frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.3)\left(\frac{W}{h}+0.8\right)}$

Width of the patch: $W = c\left[\frac{(\varepsilon_r+1)}{4f_0}\right]$

Effective length of the patch: $L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}}$

Truncation ratio: $\frac{\Delta S}{S} = \frac{1}{2Q_0}$ Where $Q_0 = \frac{c\sqrt{\varepsilon_r}}{4f_0 h}$

Truncation length of the patch:

$$m = L\sqrt{\frac{\Delta S}{S}} \tag{2}$$

Thus, the original values of length of upper patch lp and length of lower patch lp1 were calculated according to (1), where f_0 is the resonant frequency, h is thickness of dielectric substrate and ε_{eff} is the effective dielectric constant of the patch antenna. The lengths of two square patches and thickness of air layer between two substrates are optimized in simulator software ansoft HFSS 17.0 to get better return loss at dual resonating frequencies. The upper square patch length l_p is resonating at S-band frequency (2.492 GHz) and lower square patch length l_{p1}= a×l_p is resonating at L5-band frequency (1.176 GHz). Where a is the ratio of lower patch length to upper patch length which is initially selected as the ratio between two operating frequencies implying a = 2.12. The ground plane and size of both the substrates are 120×120 mm^2. The material Roger RT/duroid 5880 (ε_r =2.2) is selected as dielectric substrates for both upper and lower patch antenna in proposed design.

The RHCP operation at dual band frequencies is obtained with the help of square notches being cut along the diagonal of lower square patch and single corner truncation along the diagonal of upper square patch. Which when stacked upon each other and excited by single feed along the central axis of both the patches generate two orthogonal modes resonating along two unequal length diagonals of each patch. These generated modes in each patch are in time-phase quadrature as well along with spatial quadrature and thus producing CP radiation at both the resonating frequencies of two patches. Initial value of corner truncation lengths for both patches have been calculated using (2).

3. PARAMETRIC ANALYSIS AND OPTIMIZATION OF IRNSS ANTENNA

The proposed dual band CP antenna is modelled and simulated using ansys high frequency structure simulator (HFSS) 17.0 software. In order to design the dual-band antenna providing circular polarization over wide beamwidth, a detailed parametric study and optimization of the design variables of antenna has been carried out using HFSS simulation software. Initially the ratio between two patch lengths was kept same as the ratio of dual resonating frequencies which however obtained resonance only at lower L5 resonating frequency (1.176 GHz). By decreasing the ratio, resonance at upper S resonating frequency (2.492 GHz) become dominant. As derived from Table 1, at one particular in between value of ratio a, the dual resonating frequencies with maximum impedance match was obtained.

The simulated plot of return loss for different values of the air layer thickness between two substrates is shown in Figure 3. It is observed that the air layer thickness t affects mostly the impedance matching and impedance bandwidth of S band resonating frequency because the air layer effectively increases the substrate thickness for top SMPA. The appropriate value of t provides better tuning at S-band frequency. With the parametric variation of the lengths of corner truncation of upper and lower patch, along with feed position and relative position of bottom patch, the physical dimensions of antenna have been finalized as shown in Table 2 to get the responses wide beam gain and wide beam axial ratio as per the requirements of IRNSS system.

Table 1. Tuning of dual frequencies by varying the relative size of two square patches

Ratio	Frequency response (RL in dB)	
$a = lp1/lp$	L5 band	S band
2.12	-13.61	-1.38
1.8	-2.63	-5.01
1.7	-12.86	-12.05
1.6	-0.61	-12.13

Table 2. Physical dimensions of the proposed design of dual band CP antenna

Physical parameter	Value (mm)
Upper square patch length (lp)	46
Ratio of the lengths of two square patches (a)	1.76
Thickness of top dielectric substrate (h)	1.6
Thickness of air layer between two substrates (t)	0.8
Thickness of bottom dielectric substrate (h1)	3.2
Feed position of co-axial probe (xf)	-7.8
Diameter of via-hole in bottom patch antenna	1.3
Corner truncation length on upper patch	12.17
Corner truncation length on lower patch	6.48
Offset position of bottom patch with respect to top patch	(12,0)

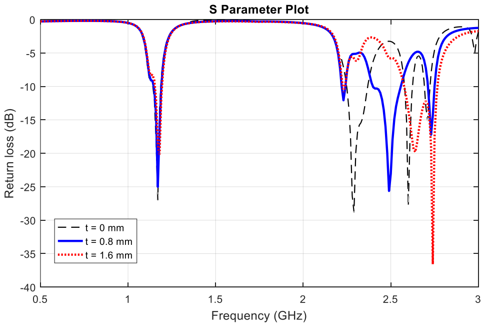


Figure 3. Simulated return loss for parametric variation of different thicknesses of an air layer

4. RESULTS AND DISCUSSION

The proposed novel series fed dual band stacked microstrip patch antenna achieves the wide beamwidth RHCP at dual band frequencies intended for receiving the navigational signals of IRNSS system with planar profile. The antenna is also suitable for modern strategic wireless communication systems related applications where dual resonating frequencies can be tuned out by varying the air gap thickness and/or varying the ratio between two patch lengths. For the designed antenna in this paper, the parameters under variation and optimization are thickness of substrate, an air gap thickness, feed position, ratio between two patch lengths and sizes of corners being truncated of square patches. The detailed results are discussed in following subsections.

4.1. Return loss (S11) and gain

The simulated return loss response (S11) of the proposed novel series fed dual band CP antenna is shown in Figure 4. Which obtains the return loss of -22.25 dB and -23 dB at L5 band and S band frequencies respectively. The impedance bandwidth obtained at first resonating frequency 1.176 GHz is 50 MHz in L5-band and at second resonating frequency 2.492 GHz is 110 MHz in S-band. These RL bandwidths are around 2.55% and 2.2% of the centre frequencies of dual band operation and hence satisfying the IRNSS antenna design requirements.

The simulated gain response at both operating frequencies (L5 and S-band) of the proposed novel series fed dual band CP antenna is shown in Figure 5. The boresight gains at L5 and S band frequencies are 8.57 and 7.03 dBi respectively owing to the fact that RT-duroid dielectric substrate material possess minimum loss tangent and hence providing better radiation efficiency at both dual band frequencies. The radiation pattern symmetry is also accomplished for dual resonating frequencies of navigational satellite system.

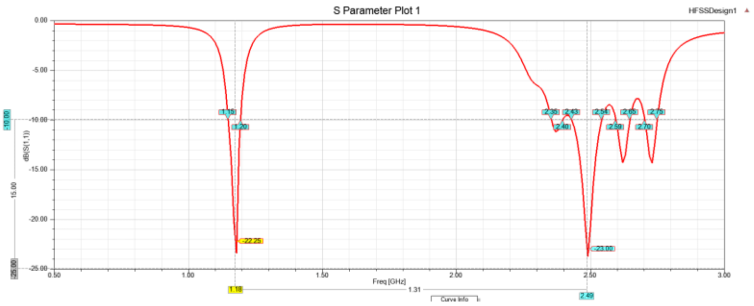


Figure 4. Simulated plot of return loss vs frequency for the proposed IRNSS antenna

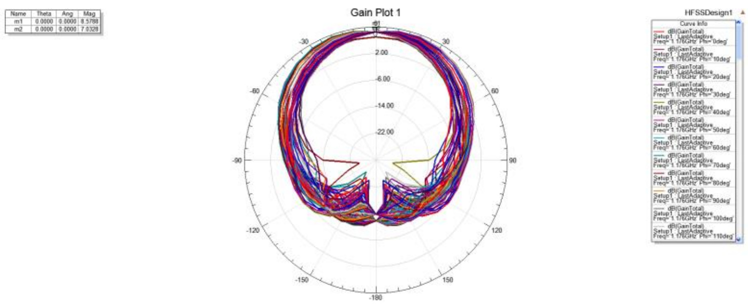


Figure 5. Simulated plot of gain vs beam angle for the proposed IRNSS antenna

4.2. Axial ratio (AR)

The simulated axial ratio at both operating frequencies (L5 and S-band) of the proposed novel series fed dual band CP antenna is shown in Figure 6. Which obtains the axial ratio of 1.03 at boresight and 1.16 at θ=60° for L5 band frequency. Hence the pure circular polarization is achieved for a wide beamwidth of 120° for L5 band frequency. The proposed antenna achieves axial ratio of 1.94 at boresight and 1.9 at θ=30° for S band frequency. Hence the pure CP is achieved for a wide beamwidth of 60° for S band frequency. As well the value of axial ratio is maintained below 3 over wide beam of angular extent of ± 60° at both L5 and S band frequencies. Which means that the proposed antenna can provide pure RHCP operation at both

the frequencies for large angular extent. Which is required for signals coming from satellites as those kinds of signals may undergo Faraday's rotation effect and can come from any direction and in any plane angle.

4.3. Co-polar and cross-polar pattern

The simulated RHCP and left hand circular polarization (LHCP) gains of the proposed antenna at L5 and S band frequencies is shown in Figure 7. The cross-polarization discrimination (XPD) factor is 16 dB and 12 dB at L5 and S band frequencies respectively. The value of XPD above 10 dB is required to keep the axial ratio below 2, which is specifying the purity of circular polarization. This is the main requirement for the navigational satellite receiving antennas which prefer the circularly polarized antennas for transmission and reception of navigational signals.

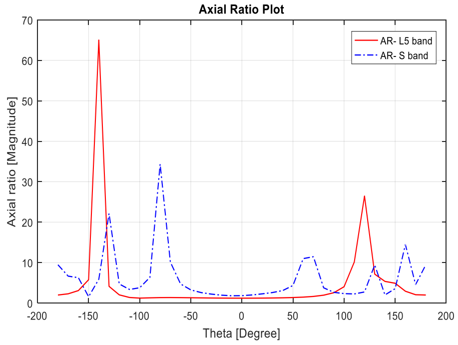


Figure 6. Simulated axial ratio vs beam angle

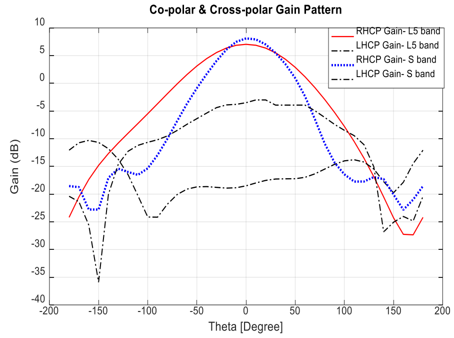


Figure 7. Simulated RHCP and LHCP gain

4.4. Axial ration beamwidth (ARBW) and voltage standing wave ratio (VSWR)

The AR performance over wide range of frequencies for the proposed dual band CP antenna intended to receive IRNSS signal is shown in Figure 8. The 3 dB axial ratio bandwidth (ARBW) is 20 MHz and 80 MHz at L5 and S band frequencies respectively. For the intended bandwidth at L5 and S band frequencies, the 3 dB axial ratio is maintained. The Figure 9 shows the graph of VSWR versus frequency for the proposed antenna. The VSWR values are 1.61 and 1.19 at the center frequencies of 1.176 GHz (L5-band) and 2.492 GHz (S-band) respectively which implies maximum signal reception at the dual band frequencies for IRNSS system.

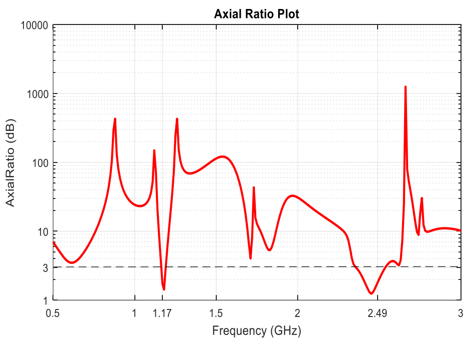


Figure 8. Simulated axial ratio vs frequency

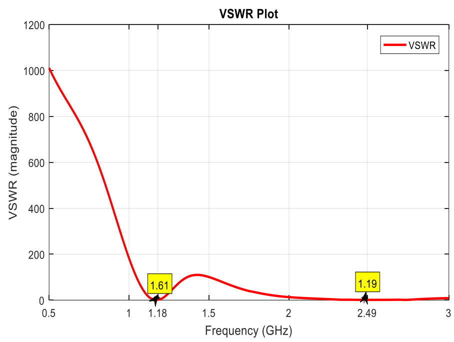


Figure 9. Simulated VSWR vs frequency

4.5. Technical specifications of proposed antenna

The obtained values of radiation parameters of the proposed novel dual band CP antenna are presented in Table 3. The proposed solution of dual band CP stacked patch antenna is able to meet the strict design criterion of IRNSS system operating at widely spaced dual band frequencies, along-with it is simple to fabricate and light in weight than other counterpart solutions (viz. spiral antennas and dielectric resonator antennas) which makes it suitable to be used for various mobile ground terminal applications. As an RF antenna designer for navigational satellite system such as GNSS, major focus should be on obtaining pure CP operation at distinguished dual frequencies to provide better position accuracy to the end users. To achieve pure CP at dual frequencies involves the higher iterations and complex optimization are required to be performed among the physical parameters of the antenna.

Table 3. Obtained radiation parameters of the proposed dual band CP antenna

Frequency (GHz)	10 dB RLBW (MHz)	VSWR	Gain (dBi)	Gain @±60º	AR	AR @±30º	AR @±60	3 dB AR BW (MHz)
1.176	50	1.61	8.57	2.44	1.03	1.1	1.16	20
2.492	110	1.19	7.03	1.16	1.94	1.81	2.91	80

Table 4. Comparison with existing designs for dual band CP antenna

Ref. antenna	Multiband operation	Centre frequencies	Freq. Ratio	10 dB RL BW	Gain at zenith	3 dB AR beamwidth	Ground plane size
[8]	tri band (L1, L2, and L5 band)	1.575, 1.227, and 1.176 GHz	1:1.3	2%, 1.5%, and 1.7%	5.6, 5.6, and 6.3 dBi	172º, 161, and 205º	80×80 mm^2
[11]	dual band (both S-band)	2.068 and 2.3875 GHz	1:1.2	~1%	4.49 and 4.81 dBi	120º and 120º	53×53 mm^2
[19]	dual band (L1 and L5 band)	1.575 and 1.176 GHz	1:1.3	3.5%, 2.1%	6.1 and 5.9 dBi	85.9 and 81.9º	114×114 mm^2
[22]	tri band (2 L band and S-band)	1.57, 1.61, and 2.49 GHz	1:1.7	0.64%, 0.93%, and 0.64%	above 0 dBi	not given	414×44 mm^2
Proposed design	dual band (L5 and S-band)	1.176 and 2.492 GHz	1:2.1	2.6%, 2%	8.57 and 7.03 dBi	120º and 60º	120×120 mm^2

As derived from Table 4, the proposed design achieves the largest frequency ratio (1:2.1) among dual resonating frequencies in Lower spectrum of microwave bands (preferred by GNSS) with wide beam CP and wide beam gain characteristics with nearly compact antenna dimensions. The novel results suggest that the single probe fed stacked corner truncated microstrip patch antenna with slight modification in stacking of two substrates can achieve the two distinguished resonating frequencies (dual band) with each maintaining wide beam gain and wide beam CP operation independently. The future work can include placement of SMPA over reactive impedance surface (RIS) to further miniaturize the physical dimensions of antenna.

5. CONCLUSION

A new single-series feed dual-band CP stacked microstrip patch antenna working at dual frequencies with a large frequency ratio has been proposed for the receiver antenna of a navigational satellite system. The structure provides dual band resonance with good circular polarization and better gain characteristics over wide beam width of 120°. The proposed antenna can be a suitable candidate for dual band RHCP antenna choice for IRNSS system. Further analysis can be done in future to reduce the overall size of the antenna which is required for compact ground terminal application of IRNSS receiver such as in military helmet or vehicle tracking system.

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